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Assessing rates of forest change and fragmentation in Alabama, USA, using the vegetation change tracker model

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ABSTRACT

Forest change is of great concern for land use decision makers and conservation communities. Quantitative and spatial forest change information is critical for addressing many pressing issues, including global climate change, carbon budgets, and sustainability. In this study, our analysis focuses on the differences in geospatial patterns and their changes between federal forests and nonfederal forests in Alabama over the time period 1987–2005, by interpreting 163 Landsat Thematic Mapper (TM) scenes using a vegetation change tracker (VCT) model. Our analysis revealed that for the most part of 1990 s and between 2000 and 2005, Alabama lost about 2% of its forest on an annual basis due to disturbances, but much of the losses were balanced by forest regeneration from previous disturbances. The disturbance maps revealed that federal forests were reasonably well protected, with the fragmentation remaining relatively stable over time. In contrast, nonfederal forests, which are predominant in area share (about 95%), were heavily disturbed, clearly demonstrating decreasing levels of fragmentation during the time period 1987–1993 giving way to a subsequent accelerating fragmentation during the time period 1994–2005. Additionally, the identification of the statistical relationships between forest fragmentation status and forest loss rate and forest net change rate in relation to land ownership implied the distinct differences in forest cutting rate and cutting patterns between federal forests and nonfederal forests. The forest spatial change information derived from the model has provided valuable insights regarding regional forest management practices and disturbance regimes, which are closely associated with regional economics and environmental concerns.

1. Introduction

Forest ecosystems have long been recognized as having global conservation importance due to their vital economic, social and environmental benefits. However, these ecosystems are being rapidly degraded or endangered in many regions of the world. Forests in the eastern United States have been dramatically transformed over the last 300 years. These forests were widely logged for agriculture through the mid 1800s, and farmland was subsequently abandoned and allowed to become reforested through natural successional processes (Cronon, 1983; Foster et al., 1998; Pinder and Rea, 1999). Particularly, in the past four decades, eastern forests have increasingly faced two major anthropogenic disturbances: timber harvesting and permanent conversion due to land use change (McDonald et al., 2006). Accurate mapping or quantifying forest changes in structural characteristics and geospatial distributions induced by natural or anthropogenic disturbances is of great interest for land use decision makers and conservation communities to address many pressing issues including global climate change and carbon budgets, sustainability, and the vulnerability of natural and human systems (Band, 1993; Schimel, 1995; Laurance, 2000; Zhang et al., 2001). Such forest changes are related to forest fragmentation, which is generally defined as the process of subdividing a continuous habitat type into a series of compact, more isolated and smaller patches, resulting in diverse impacts on ecological processes (Schwartz, 1997; Turner et al., 2001). Notably, one of the most alarming aspects of forest loss and fragmentation is the unparalleled threat to biodiversity (Laurance, 1999), which can increase the risk of species extinction. Currently, exploring the effects of forest loss and fragmentation on ecological processes and function at diverse scales (local, regional, national and global) is of

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primary concern for sustainability when managing forests around the world (Abdullah and Nakagoshi, 2007).

The 2007 annual report compiled by the Alabama Forestry Commission (available at http://www.forestry.state.al.us/publication/PDFs/NewAnnualReport.pdf) and the report of Forest Facts of Alabama (available at http://www.forestry.alamaba.gov/publication/forest_facts.htm) argue that Alabama's forests provide adequate economic, recreational, environmental, and social resources to each Alabamian and its rich population of plants and animals. At present, forests cover 71% of Alabama or 9,307,769 ha. About 95% of Alabama's forests are privately owned, with only 5% owned by the government. Pinder and Rea (1999) concluded that in the eastern United States, the large proportion of forest in private ownership has brought about problems in the management and maintenance of forest resources due to (1) the importance of economic forces in determining the fate of privately owned forest (Adams et al., 1996) and (2) the limited replacement and regeneration of harvested areas on private lands. Additionally, the report of United States forest facts and historic trends (available at http://www.fia.fs.fed.us/library/briefings-summaries-overviews/docs/ForestFactsMetric.pdf) concludes that the national timber production appears to be shifting from public land to private land. In 1996, private forests provided 89% of the national timber harvest, but 95% of private forests did not have a written management plan and not all forest activities were well documented.

The report of Forest Facts of Alabama documents that there are about 440,000 timber ownerships and nearly 50% of all forest owners manage forests less than 202 ha in size. This fact implies a heavily fragmented administration for the forests. There are over 1100 forest manufacturing operations and about 100,000 workers indirectly or directly dependent upon the forest industry, suggesting that frequent forest logging and regeneration operations exist in Alabama to sustain the forest-dependent industry. In addition, the existing forests support 1.4 million of the nation's 18 million white-tailed deer and 350,000 of its 4 million wild turkeys. The division of the forest into small private land holdings, the importance of economic forces in determining forest logging and the relatively poor management of forests on private lands imply a fragmented forest landscape

Unfortunately, at the state level, few researchers have characterized how the forest landscape has changed as a consequence of forest management. Failure to track the forest change patterns has already led to inadequate understanding of forest configurations and forest change trends. Therefore, analyses of rates and patterns of forest landscape change are needed to better understand how management practices and natural disturbances (e.g., fires and tornadoes) affect important forest habitat characteristics, such as amount of edge and interior habitat and patch size, and to provide a basis for making management and policy decisions.

The purpose of this study was to use a historical record of 163 Landsat Thematic Mapper (TM) scenes to characterize forest spatial configurations at a 3-yr time interval over the time period 1987–2005 in Alabama. Specifically, the study was to (1) develop forest change products using a vegetation change tracker (VCT) model, (2) characterize rates of forest change by land ownership, (3) compare fragmentation patterns and dynamics between federal and nonfederal forest landscapes and create a multi-temporal profile of forest fragmentation at the state scale, and (4) identify the statistical relationships between forest fragmentation and forest change.

2. Data and study area

Fig. 1 illustrates the location of the study area, Alabama, USA. The shaded areas represent the federal lands. The study area extends from 84.85° to 88.47° West longitude and 30.22°–35° North latitude, with a land area of 135,775 km^2, supporting a population of about 4.5 million. Elevations range from 0 along the coast to 733.7 m above sea level in the northeast with a mean elevation of 152.4 m. Monthly average temperatures range from a high of 33.1 °C to a low of −1.1 °C. Major forest types include loblolly-shortleaf pine, longleaf-slash pine, oak-gum-cypress and oak-hickory-pine.

The reasons for selecting Alabama as our study area were threefold. First, Alabama's forests are extremely vital to Alabama's economy (see the Forest Facts of Alabama, mentioned above). Second, forest change occurs frequently in Alabama due to forest harvesting and reforestation practices to ensure a sustainable supply of sawtimber and pulpwood to the processing industry of forest-dependent products (McDonald et al., 2006). However, to date, our understanding of forest spatiotemporal change patterns at the state scale remains unclear. Third, thanks to the ongoing national LANDFIRE project (http://www.landfire.gov/), 163 Landsat TM scenes were available for assessing forest change over Alabama.

Twelve Landsat path/rows cover the administrative boundaries of Alabama (Table 1). To select the proper Landsat scenes for subsequent analysis, we applied two rules for the selection. The rules concerned the cloud cover and acquisition date of each TM scene. In this case, we excluded those scenes that had over 30% cloud cover or were acquired on November through March (Table 1). The intent of applying the acquisition date rule was to ensure a proper capture of spectral signatures under leaf-on conditions. Thus, 163 Landsat scenes were eventually selected and stacked by path/row to enable our derivation of forest change information using the VCT model. Additionally, the National Land Cover Database (NLCD) 2001 was downloaded from http://www.mrlc.gov to support the delineation of the training dataset for forest class based on the input TM imagery when running the VCT model.

3. Methods

3.1. Description of the VCT model

VCT is an automated forest change mapping algorithm designed for analyzing dense time series stacks of Landsat images as listed in Table 1. It consists of two major steps: individual image analysis and time series analysis. During the individual image analysis step, forest samples are identified and used to calculate a suite of indices. Once this is done for all images of a stack, the indices are used to construct temporal profiles for each pixel and forest changes are mapped through the time series analysis step. A brief description of the VCT algorithm can be found in Huang et al. (submitted for publication).

3.2. Derivation of forest change information

Individual forest spatiotemporal change products were developed for each image stack by employing the VCT model. The model produces four groups of datasets, including the change flags, the selected attributes of mapped changes, indices and masks. In this study, we focused our attention on the forest disturbance (loss) datasets from the second group. Specifically, each disturbance map shows where forest loss areas occurred in a particular year. Simultaneously, this map also represents another six classes (values). The detailed descriptions of the disturbance map are summarized in Table 2.

3.3. Aggregation of the forest disturbance map

First, to focus on the analytical pattern of forest versus nonforest, the original seven classes in the disturbance map were

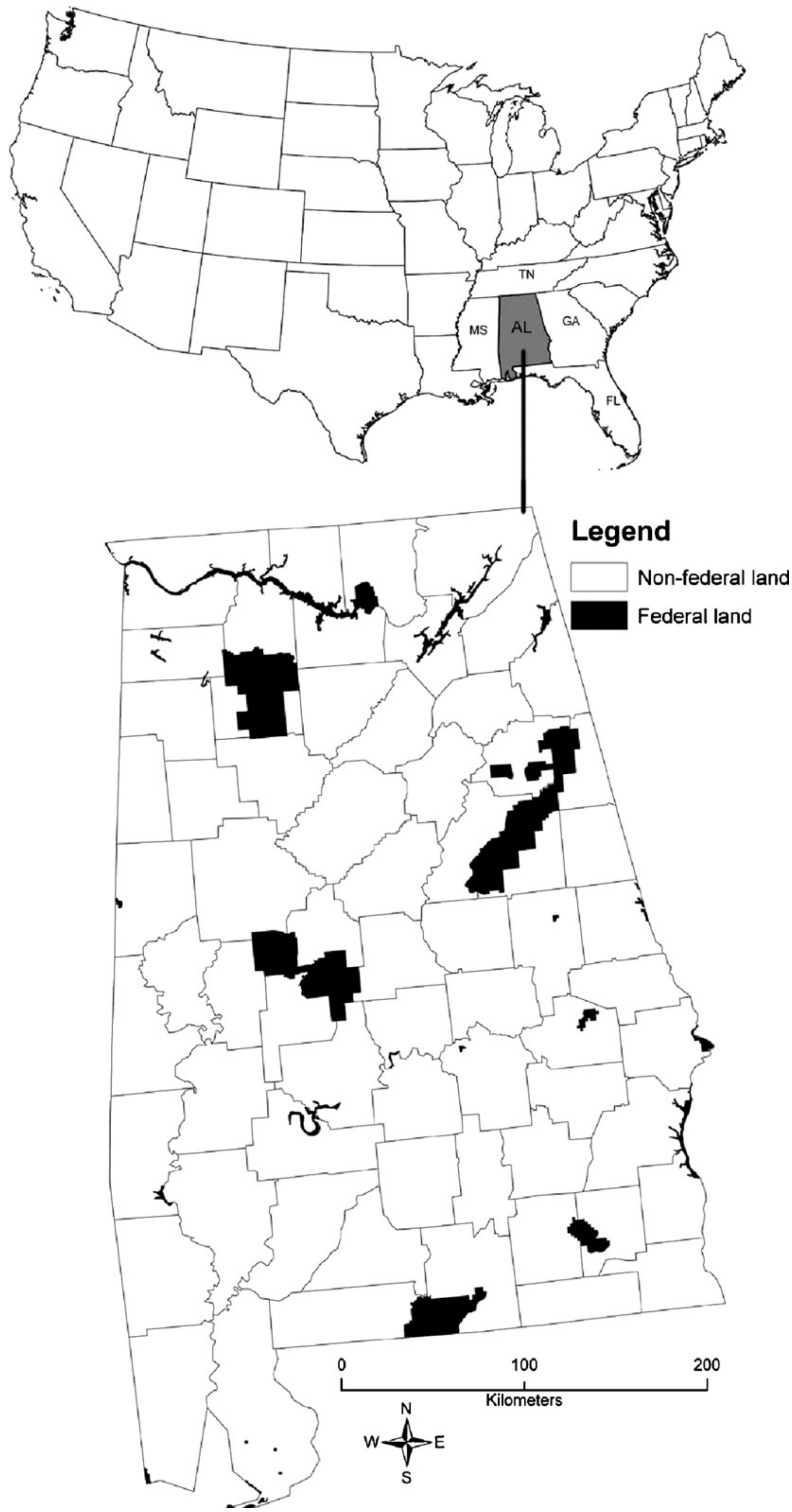

Fig. 1. Location of the study area, Alabama, USA. Forests on the shaded areas are termed ''federal forests or national forests''. Forests out of the federal lands are nonfederal forests.

aggregated. Table 2 illustrates the criteria for this aggregation. In detail, class 2 (persisting forest) and 5 (probable forest with recent disturbance) were aggregated into a new forest class. Class 1 (persisting nonforest), 6 (disturbed in this year) and 7 (post-disturbance nonforest) were grouped into the nonforest class. Notice here if a disturbance is followed by regeneration, a pixel will transition from class 7 to class 5. In the VCT algorithm this transitioning point is determined when the algorithm detects consecutive forest signals as indicated by the indices used by this algorithm, which is typically 5–8 years following a disturbance in Alabama. The persisting water was kept unchanged in the aggregation. Once this thematic aggregation was made, we then aggregated the disturbance maps temporally prior to creating mosaics for the entire state. Specifically, we identified seven

Table 1
List of Landsat TM scenes involved in the development of forest change information over Alabama, USA.

Path/row	Acquisition date
19/37	06/04/1984, 06/26/1986, 10/03/1987, 10/05/1988, 06/05/1990, 06/08/1991, 07/31/1993, 10/09/1995, 10/11/1996, 06/27/1998, 09/28/2000, 10/01/2001, 09/29/2003, 08/14/2004, 09/02/2005
19/38	06/04/1984, 10/16/1986, 05/30/1988, 06/05/1990, 06/08/1991, 07/31/1993, 10/09/1995, 10/11/1996, 06/27/1998, 10/14/2000, 10/01/2001, 80/09/2002, 08/14/2004, 10/07/2006
19/39	06/04/1984, 04/23/1986, 04/26/1987, 06/15/1988, 04/18/1990, 06/08/1991, 07/31/1993, 10/09/1995, 05/20/1996, 06/27/1998, 07/16/2002, 04/22/2003, 04/27/2005
20/36	06/27/1984, 07/19/1986, 07/08/1988, 06/12/1990, 09/03/1991, 08/23/1993, 07/12/1995, 09/19/1997, 11/04/1999, 09/19/2000, 06/18/2001, 06/21/2002, 09/22/2004, 09/09/2005, 06/24/2006
20/37	06/11/1984, 07/19/1986, 07/08/1988, 07/30/1990, 07/01/1991, 08/23/1993, 05/22/1994, 7/30/1996, 09/19/1997, 07/23/1999, 05/14/2000, 10/08/2001, 06/13/2002,09/22/2004
20/38	06/11/1984, 07/19/1986, 07/08/1988, 06/28/1990, 07/22/1993, 06/10/1995, 08/18/1997, 09/17/1999, 06/18/2001, 10/22/2003, 09/28/2006
20/39	10/01/1984, 07/19/1986, 07/08/1988, 06/28/1990, 10/23/1992, 05/22/1994, 06/10/1995, 09/19/1997, 09/17/1999, 04/18/2002, 04/13/2003, 04/15/2004, 04/05/2006
21/36	06/18/1984, 09/28/1986, 06/13/1988, 06/19/1990, 09/26/1991, 10/01/1993, 10/07/1995, 08/25/1997, 08/17/2000, 10/15/2001, 08/07/2002, 05/08/2004, 05/27/2005, 06/15/2006
21/37	09/06/1984, 06/27/1987, 06/13/1988, 09/07/1990, 09/26/1991, 10/01/1993, 06/17/1995, 08/25/1997, 09/16/1999, 09/29/2001, 06/23/2003,10/18/2005
21/38	09/06/1984, 06/24/1986, 06/27/1987, 10/22/1989, 06/19/1990, 09/26/1991, 10/01/1993, 10/07/1995, 08/25/1997, 08/15/1999, 07/08/2000, 10/15/2001, 08/07/2002, 10/29/2003, 10/15/2004, 05/27/2005
21/39	09/06/1984, 06/24/1986, 06/27/1987, 10/22/1989, 09/26/1991, 10/01/1993, 10/07/1995, 08/25/1997, 08/15/1999, 10/15/2001, 10/18/2002, 10/15/2004
22/36	10/31/1984, 07/17/1986, 09/08/1988, 07/28/1990, 07/31/1991, 06/18/1993, 08/27/1995, 10/03/1997, 08/06/1999, 08/16/2000, 04/29/2001, 07/05/2002, 08/19/2004, 08/22/2005

sampling time points at 1987, 1990, 1993, 1996, 1999, 2002 and 2005, respectively, and aggregated the original disturbance maps that had a quasi biennial interval (see Table 1) to maps having a 3-year interval. This resulted in disturbance maps that were temporally consistent among different path/rows, from which mosaics for the entire state were created. Thus, a time series of forest change maps covering Alabama's territory was obtained.

3.4. Computation of the landscape metrics

Quantification and comparison of spatial metrics have been recognized as the most effective way to assess forest fragmentation (Pinder and Rea, 1999; Fitzsimmons, 2003). In the present study, after reviewing recent forest fragmentation studies (Fuller, 2001; Staus et al., 2002; Butler et al., 2004; Abdullah and Nakagoshi, 2007; Li et al., 2008), we selected a suite of metrics to assess forest fragmentation status and trends that have been widely applied in diverse types of landscapes and have enabled the assessment of spatial attributes in fragmented landscapes. The indices included the core area index (CAI), edge density (ED), largest polygon index (LPI) and mean polygon area (MPA). These spatial metrics were computed for federal forests and nonfederal forests in Alabama using the Image Analyzer (IAN) program, which was developed at the University of Wisconsin and is available at http://forest-landscape.wisc.edu/projects/ian/.

3.5. Implementation of the forest fragmentation model

Besides the geospatial metrics, we used the forest fragmentation model outlined in Riitters et al. (2000, 2002) to develop maps depicting six forest fragmentation components (interior forest, perforated forest, edge forest, patch forest, transitional forest and undetermined forest) for both federal forests and nonfederal forests because this model has proven to be an effective alternative in characterizing forest fragmentation at diverse scales (Hurd et al., 2001; Riitters et al., 2002; Wade et al., 2003). Prior to running the model, two indices, P_f and P_{ff}, were derived, where P_f is the proportion of nonmissing pixels within the moving window with a specified size that are forest, and P_{ff} is the ratio of the number of pixel pairs in cardinal directions that are both forest divided by the number of pixel pairs in cardinal directions where either one or both are forested. Roughly, P_{ff} measures the conditional probability that a pixel adjacent to a forest pixel is also forest. Once the P_f and P_{ff} were available, each subject forest pixel centered within the moving window was classified into one of six forest fragmentation categories described previously by applying the discriminant rules defined by the fragmentation model. Because the outcomes of the model are scale–dependent and threshold-dependent (Riitters et al., 2000, 2002), to maintain a fair representation of the proportion (P_f) of pixels in the window and to maintain interior forest at an appropriate level, a moving window with the size of 5 by 5 pixels was ultimately determined to be appropriate for analyzing the fragmentation. Thus, an image having a 2-pixel wide (60 m) border could be generated to properly represent the actual characteristics of forest fragmentation in southeastern United States.

Table 2
Definition and aggregation of forest disturbance map.

Value	Class description in VCT model	Aggregated class
0	Background	Abandoned
1	Persisting nonforest	Nonforest
2	Persisting forest	Forest
4	Persisting water	Water
5	Probable forest with recent disturbance	Forest
6	Disturbed in this year	Nonforest
7	Post-disturbance nonforest	Nonforest

4. Results

4.1. Analysis of forest changes

Changes in Alabama's forests are of particular concern for local authorities to adequately understand how forest management practices, wildfires and tornados affect the geospatial distribution of the forests. In this case, forest change estimates for federal and nonfederal forests were derived and summarized in Table 3. The table shows that the nonfederal forest is predominant in area share compared with the federal forest (about 95% versus 5%) and the comparative patterns remain almost stable over time. Examining the forest annual loss rate, we can find that nonfederal forest rate of loss is much higher than for federal forests during all the time intervals. Nonfederal forest loss is almost double federal forest loss during four time intervals. Exceptions are the two time intervals, 1990–1993 and 1993–1996. Similarly, when checking the forest annual net change rate, nonfederal forest change rate is higher

Table 3
Alabama's forest disturbances derived from the VCT model.

Time interval	Forest area at the start of the interval (ha)	Forest area at the end of the interval (ha)	Forest area lost (ha)	Forest area added (ha)	Forest annual loss rate (%)	Forest annual net change rate (%)
Nonfederal forests						
1987–1990	7,650,820	7,873,650	306,717	529,099	1.34	0.97
1990–1993	7,873,650	8,132,710	350,481	610,328	1.48	1.10
1993–1996	8,132,710	7,957,320	540,438	363,070	2.22	−0.73
1996–1999	7,957,320	7,919,780	509,331	471,158	2.13	−0.16
1999–2002	7,919,780	7,698,180	680,367	460,576	2.86	−0.93
2002–2005	7,698,180	7,473,360	496,758	272,419	2.15	−0.97
Federal forests						
1987–1990	513,626	527,498	10,556	24,427	0.69	0.90
1990–1993	527,498	532,101	17,172	19,880	1.09	0.17
1993–1996	532,101	520,501	22,313	12,609	1.40	−0.61
1996–1999	520,501	526,357	17,735	23,591	1.14	0.38
1999–2002	526,357	519,315	22,252	15,210	1.41	−0.45
2002–2005	519,315	510,417	16,107	7,210	1.03	−0.57
Statewide forests						
1987–1990	8,164,446	8,401,148	317,273	553,526	1.30	0.96
1990–1993	8,401,148	8,664,811	367,653	630,207	1.46	1.04
1993–1996	8,664,811	8,477,821	562,751	375,679	2.16	−0.72
1996–1999	8,477,821	8,446,137	527,066	494,749	2.07	−0.13
1999–2002	8,446,137	8,217,495	702,619	475,786	2.77	−0.90
2002–2005	8,217,495	7,983,777	512,865	279,629	2.08	−0.95

Notes: Forest annual loss rate is defined as (forest area lost/forest area at the start of the interval) and forest annual net change rate is defined as ((forest area added − forest area lost)/forest area at the start of the interval).

than for federal forests for most time intervals, with the exception of the time interval between 1996 and 1999. During this interval, forest annual net change rate of nonfederal forest is identified as −0.16% whereas federal forest is observed at 0.38%. For the other five time intervals, federal forest and nonfederal forest show similar changing trends, with different rates (Table 3). All above comparisons between federal forests and nonfederal forests suggest that nonfederal forest in Alabama has been heavily disturbed while federal forest remains less disturbed.

4.2. Forest fragmentation characterized by geospatial metrics

Table 4 summarizes the measurements of four geospatial metrics for federal forest and nonfederal forest. Changes in forest area are accompanied by changes in the forest patch statistics at the identified sampling time points (Table 4), and the patterns of these changes differ between federal forest and nonfederal forest. First, significant changes in the spatial pattern for the nonfederal forests were observed since 1987. The LPI increased from 19.90% in 1987 to 28.61% in 1993, connecting to a gradual decrease between 1994 and 2005. Notably, in 2005, the LPI reached to 10.78%, which is less than the half of the peak value of 28.61% in 1993. There was a weak increase in CAI between 1987 and 1993, however, after 1993, the CAI declined and the lowest value was recorded at 66.43% in 2005. ED decreased in the early stage of forest change but increased during the later stages. Conversely, MPA increased in the early stage but decreased during the later stages. Some changes in fragmentation statistics for the federal forests were also identified. However, in contrast, their fragmentation trend appeared to be somewhat vague for some metrics, for example, ED and MPA. Comparing the fragmentation severities between federal forests and nonfederal forests suggests that federal forests are less fragmented than nonfederal forests at the seven time points. Temporally, nonfederal forests show a clear trend in fragmentation, which is characterized by a gradual decreasing fragmentation during the time period 1987–1993 connecting to an increasing fragmentation during the time period 1994–2005.

4.3. Forest fragmentation depicted by fragmentation model

Forest fragmentation statistics were derived from the fragmentation maps after implementing the fragmentation model using a window size of 5 by 5 pixels (Fig. 2). The graph shows a similar fragmentation for both federal forests and nonfederal forests. First, the interior forest component shows a gradually increasing trend between 1987 and 1993 giving way to a decreasing status over the time period 1994–2005. Second, perforated forest and edge forest conditions show a formerly decreasing trend between 1987 and 1993 connecting to a subsequent increase over the time period 1994–2005. Third, the other three fragmentation components remain relatively steady over time. These observations derived from the fragmentation

Table 4
Comparison of forest fragmentation characterized by four geospatial metrics between federal forests and nonfederal forests in Alabama over the time period 1987-2005.

Metrics		1987	1990	1993	1996	1999	2002	2005
Core area index (%)	Federal	82.23	83.26	83.52	81.16	82.27	81.46	79.87
	Nonfederal	72.77	73.50	73.64	71.12	71.11	68.91	66.43
Edge density (m/ha)	Federal	61.78	56.91	57.30	64.81	60.74	63.91	68.94
	Nonfederal	99.76	95.80	94.81	103.84	104.14	113.58	123.26
Largest polygon index (%)	Federal	21.25	21.80	21.66	21.39	21.34	20.17	19.11
	Nonfederal	19.90	20.83	28.61	23.50	17.74	17.15	10.78
Mean polygon area (ha)	Federal	60.09	68.40	74.88	69.03	62.93	64.59	58.74
	Nonfederal	28.73	32.21	38.70	34.21	34.01	28.42	24.98

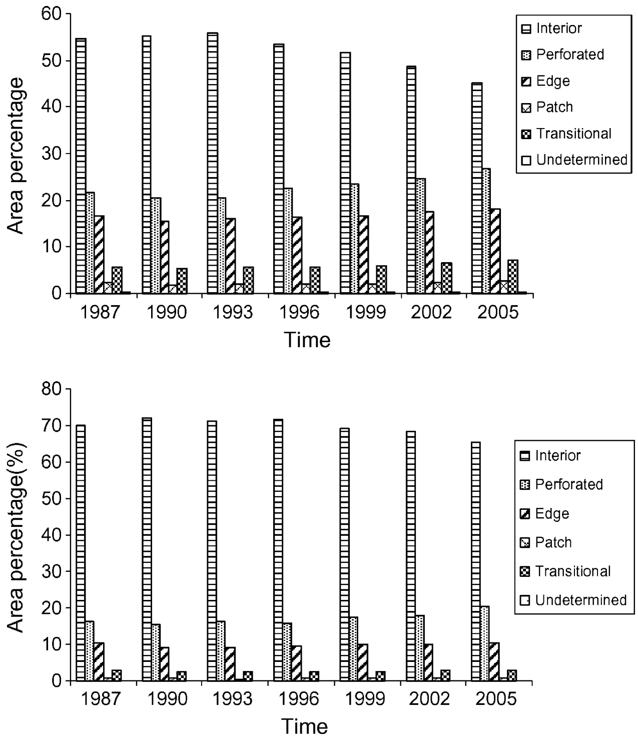

Fig. 2. Comparison of forest fragmentation patterns, derived from implementing the fragmentation model at the window size of 5 by 5 pixels. Upper: nonfederal forest fragmentation; lower: federal forest fragmentation.

model are in agreement with our interpretations of four geospatial metrics, mentioned above. Together, derivations from both the fragmentation model and geospatial metrics commonly demonstrate that both federal forests and nonfederal forests follow a similar fragmentation trend: a formerly decreasing fragmentation between 1987 and 1993 giving way to an accelerating fragmentation over the time period 1994–2005. Additionally, Fig. 2 conveys that the fragmentation severities of nonfederal forests are much higher than federal forests, by comparing the area shares of six fragmentation components at the seven time points.

5. Discussion

5.1. Forest area

In this analysis, time sequential forest area statistics for Alabama were estimated at 8,164,446 ha, 8,401,148 ha, 8,664,811 ha, 8,477,821 ha, 8,446,137 ha, 8,217,495 ha and 7,983,777 ha for 1987, 1990, 1993, 1996, 1999, 2002 and 2005, respectively. However, the official estimates are 8,791,796 ha, 8,903,084 ha, 8,888,515 ha, 9,307,770 ha, 9,302,509 ha and 9,185,834 ha for 1987, 1990, 1997, 2000, 2002 and 2005 (see the Forest Inventory & Analysis Factsheet Alabama 2004, available at http://srsfia1.fia.srs.fed.us/states/al/AL2004~1.pdf, the List of Tables compiled by the USDA Forest Service 2003, available at http://ncrs2.fs.fed.us/4801/fiadb/rpa_tabler/Draft_RPA_2002_Forest_Resource_Tables.pdf, and the Forest Resource Report 2006 compiled by Alabama Forestry Commission. available at http://www.forestry.alabama.gov/publication/PDFs/Forest_Resource_2006.pdf). Obviously, close agreement between the two suites of statistics is not expected at the coincided sampling dates and the official estimates are higher than those corresponding model-based derivations. Meanwhile, these two suites of statistics show a similar trend in forest area change: a formerly gradual increase connecting to a subsequent decreasing trend. One may attribute these discrepancies to errors in the VCT products (assuming FIA estimates are "truth"). However, an accuracy assessment of a VCT derived disturbance map revealed that despite some levels of commission and omission errors at the per-pixel level, areal estimates of nonforest and forest (including disturbances) derived from reference data differed from those calculated from the disturbance map by only 1.1% (Huang et al., submitted for publication, Table 3). The majority of the differences are likely due to differences in the definition of forested lands, as well as measurement scales and methodology. The official estimates are based on the FIA data from the USDA Forest Service, which are derived from the sampling estimation theories in conjunction with the systematically gridded field sample plots. In the official analysis, "forested land" is defined as "at least 16.7% stocked by forest trees of any size, or formerly having such tree cover, and not currently developed for "nonforest use" (Thompson, 1989). This definition means that forests which have been cut, but not regenerated, are still considered as "forested lands." However, the forest class defined in our model is fully dependent upon the detectable or separable spectral signatures of "actual forest" in a complex matrix of actual land cover types on the ground. Obviously, our estimates derived from interpreting remotely sensed imagery by means of computerized pattern recognition techniques cannot include those newly cut areas and those newly regenerated areas with sparsely dispersed trees due to the spectral confusion effects. Therefore, it is easy to understand why our estimates are lower than the official estimates. However, it needs to be noted that our derivations based on remotely sensed data reflect the real-time land cover interplay on the ground and further provide spatially explicit information, which is necessary for analyzing landscape fragmentation. In contrast, the USDA Forest Service FIA data provide little information on parameters, such as patch size, that are likely to affect the use of forest habitats by associated plants and animals (Pinder and Rea, 1999).

The Alabama Forestry Commission Annual Report 2004–2005 states that historically, there are four major drivers responsible for the loss of forested lands in Alabama, including logging operations, forest insect and diseases, wildfires and tornados. Logging operations are predominant, and our focus needs to center on these practices for the current analysis. Regions where forests were thinned (common in some areas) or burned with certain severity are easily detectable using the VCT model in association with Landsat TM imagery (30-m resolution), so less aggressive cutting methods and noncatastrophic forest fires are presented in our derivations. This is because the VCT model adequately considers the effects of relatively intensive thinning practices and cloud shadows when developing the algorithms to identify the forest changes in the southeastern United States. However, we do not know yet if the model is able to detect forest changes related to the effects of forest insect and diseases. Therefore, it is likely that actual forest area change results were slightly greater than what was mapped and summarized in this analysis.

5.2. Forest annual loss rate

Alabama's forests have undergone moderate disturbance during the time period 1987–2005 compared to many tropical forests. Forest loss in Alabama was similar on federal and nonfederal lands with nonfederal (privately and industry owned) forests showing a slightly higher rate of forest loss overall. We observed the forest annual loss rate at 1.34%, 1.48%, 2.22%, 2.13%, 2.86% and 2.15% for nonfederal forests, and the corresponding 0.69%, 1.09%, 1.40%, 1.14%, 1.41% and 1.03% for federal forests over the identified six time intervals in this analysis (Table 3). The observed differences in annual loss rate suggest that nonfederal forests are more disturbed than federal forests. Staus et al. (2002) investigated forest disturbance by ownership in the

Klamath–Siskiyou ecoregion, which covers southwestern Oregon and northwestern California, USA. They found that the major forest loss was attributed to clearcut logging in this region. Further, they reported that forest cover had the highest percentage net decrease within private ownership than any other ownership category. Their findings are consistent with our observations in Alabama. Pinder and Rea (1999) compared the forest loss rate by ownership in the Upper Coastal Plain in the southeastern United States. This area is bisected by the Savannah River, which separates South Carolina to the north from Georgia to the south. In their analysis, they found that the cutting rate of pine forest (similar to our forest annual loss) for privately owned land was 4.0% year^{-1} and was significantly greater than the 1.6% year^{-1} rate for the federal forests within the U.S. Department of Energy's Savannah River Site (SRS). Their observation of 1.6% year^{-1} rate for federal forests in SRS is slightly higher than our results. Similar to our findings, they found that nonfederal forests were more disturbed than the federal forests. Zheng et al. (1997) reported a 1.12% forest annual loss rate outside of the Changbai Biosphere Reserve in China. This result is comparable to our derivations for nonfederal forests in Alabama, albeit a slightly lower magnitude. For the statewide forests of Alabama, we derived the forest annual loss rate at 1.30%, 1.46%, 2.16%, 2.07%, 2.77% and 2.08 for the identified six time intervals. These estimates are compatible with the similar derived rates of 2.1% year^{-1} for conifer forests on nonpublic land in Oregon (Spies et al., 1994) and 2.7% year^{-1} for the Ivory Coast (Chatelain et al., 1996). In addition, in the eastern United States, Hall et al. (1991) reported annual conifer forest loss rate of 1.8% in northern Minnesota and Luque et al. (1994) found annual pine-oak forest declines in the Pine Barrens region of New Jersey to be 2.2%. These comparisons suggest that the VCT model and analytical methodology we adopted in this analysis appear reasonable.

5.3. Loss in forest area

On the other hand, forest harvest trends in Alabama also partially coincide with the trends of the derived loss in forest area in Table 3. The 2006 forest resource report compiled by the Alabama Forestry Commission and the Alabama Forestry Commission Annual Report 2004–2005 summarized the sawtimber and pulpwood harvest trends by year between 1996 and 2006, as well as the average prices for sawtimber stumpage and pulpwood stumpage by year in Alabama. In this analysis, we used the harvest trends to directly relate to our derived forest annual loss rates in Table 3. As a result, we found that between 1996 and 2005, our derived loss in forest area agrees with the trends presented by the stock volume data. Due to the unavailability of reliable harvest data for the period 1987–1995, we could not verify our corresponding loss in forest area trends.

5.4. Forest fragmentation

In the current study in Alabama, we identified that nonfederal forests were more fragmented than federal forests. Our analysis was successful in creating a dense temporal profile of forest fragmentation for Alabama. Other studies have documented deforestation and fragmentation on public and private lands in other parts of the United States. Spies et al. (1994) observed greater fragmentation of coniferous forests on private land in western Oregon. Pinder and Rea (1999) compared the fragmentation between private lands and the lands of the U.S. Department of Energy's Savannah River Site and they also concluded that private forests were largely fragmented. Staus et al. (2002) found that private forests were more fragmented than public forests in the Kamath–Siskiyou ecoregion, and forest fragmentation increased on all ownership over time. In addition, some efforts have investigated the temporal trends in forest fragmentation. Fuller (2001) interpreted a series of Landsat images from 1973, 1987 and 1999 covering a rapidly developing area of Loudoun County, Virginia, USA and determined that forest fragmentation increased over time. Cayuela et al. (2006) examined the clearance and fragmentation of tropical montane forests in the Highlands of Chiapas, Mexico using Landsat imagery from 1975, 1990 and 2000 and observed an increasing rate of fragmentation over this region. Echeverría et al. (2006) focused on the rapid deforestation and fragmentation of Chilean temperate forests and they also reported an increasing fragmentation over 25 years (1975, 1990 and 2000). In the current analysis, we identified that forest fragmentation accelerated during the time period 1994–2005. Meanwhile, unlike above studies, we observed a decelerated fragmentation in Alabama over the time period 1987–1993. This unique contribution is probably attributed to our temporally dense characterization of forest change information by means of the VCT model. Our success in densely characterizing forest fragmentation in this analysis can compensate for the inadequate characterization presented by abovementioned studies when adopting a relative long time step (e.g., almost 10 years), which may miss certain status information.

5.5. The relationships between forest fragmentation and forest management

The statistical relationships between forest fragmentation and forest logging and regeneration practices, which were represented by the forest annual loss rate and forest net change rate in this analysis, have not been addressed in previous studies. Franklin and Forman (1987) analyzed the influence of cutting pattern on the amount of edge and interior forest. In this study, we related the time series of the area shares of interior, perforated and edge components (Fig. 2) to the observations of forest annual loss rate and forest net change rate (Table 3). Table 5 summarizes the derived correlations. Comparing the determination coefficient R^2, we find that for both federal forests and nonfederal forests, forest net change rate is more effective in explaining the variability of forest fragmentation than forest loss rate. This is because forest fragmentation in itself is a product of the spatial rearrangement of a large number forest patches in a given landscape matrix. During this process, inevitably, some forest patches will disappear due to

Table 5
Statistical relationships between forest fragmentation and forest change rate.

	Forest annual loss rate (FL)	Forest annual net change rate (FN)
Interior (I)	$I = -10.306\ \ln(\text{FL}) + 58.709$ ($R^2 = 0.5041$) (NF) $I = -1.9767\ \ln(\text{FL}) + 69.834$ ($R^2 = 0.0425$) (FF)	$I = 3.5646\text{FN} + 52.172$ ($R^2 = 0.6724$) (NF) $I = 2.1661\text{FN} + 69.716$ ($R^2 = 0.2793$) (FE)
Perforated (P)	$P = 15.046\text{FL}^{0.1478}$ ($R^2 = 0.5389$) (NF) $P = 16.992\text{FL}^{0.0686}$ ($R^2 = 0.0328$) (FE)	$P = 23.003e^{-0.0831\text{FN}}$ ($R^2 = 0.6881$) (NF) $P = -1.4169\text{FN} + 17.129$ ($R^2 = 0.244$) (FE)
Edge (E)	$E = 19.631\text{FL}^{0.2493}$ ($R^2 = 0.5558$) (NF) $E = 9.6525\text{FL}^{0.0958}$ ($R^2 = 0.2353$) (FE)	$E = 16.526e^{-0.0509\text{FN}}$ ($R^2 = 0.7116$) (NF) $E = 9.7217e^{-0.0576\text{FN}}$ ($R^2 = 0.4659$)

Statistical relationships between forest fragmentation and forest change rate. Notes: (NF) stands for the nonfederal forests and (FE) denotes the federal forests.

diverse disturbances (e.g., logging and fires) and some forest tracts will be added into the landscape because of afforestation or reforestation practices. Thus, it is easier to understand that forest net change rate (including not only forest loss information but also forest regeneration information) depicts forest fragmentation more comprehensively and accurately than forest loss rate. Spies et al. (1994) argued that forest fragmentation was only one stage of forest pattern dynamics that resulted from the simultaneous operation of disturbance and regeneration, which is identical to our argument in this study. Furthermore, forest loss rate and forest net change rate have a higher power (R^2) in explaining the variability of forest fragmentation within nonfederal forests. We can identify the highest R^2 at 0.7116 when modeling forest net change rate and the edge component of nonfederal forests. Conversely, the lowest R^2 of 0.0328 was observed when relating forest loss rate to the perforated condition of federal forests (Table 5). The underlying causes leading to these distinct differences in explanatory power may be that federal forests are well protected and less disturbed whereas nonfederal forests are heavily disturbed by logging and regeneration operations. Another possible explanation is the difference in cutting pattern between federal forests and nonfederal forests. Staus et al. (2002) concluded that private lands showed a more extensive cutting approach with larger adjacent blocks of land clearcut at a time. Public lands exhibited a more dispersed cutting regime known as the "staggered-setting clearcut system" where smaller blocks of forest were cut at a time with the cut blocks dispersed over the extent of the forest. Their private lands and public lands correspond to the nonfederal lands and federal lands in our analysis.

Because the rates, patterns and total amount of forest disturbance were different between ownership types in Alabama (Table 3), our analysis demonstrated that a different pattern of forest fragmentation typically occurred on nonfederal versus federal lands (Tables 4 and 5, Fig. 2). Loss or conversion of these forests will have complex, long-term effects on regional biodiversity. For example, the red-cockaded woodpecker and (historically the ivory-billed woodpecker) and songbird are confined to old-growth (or at least more mature) forests. Obviously, they need more spacious interior forests to survive. However, some species of this region (e.g., wild turkey and deer) are well adapted to regenerating and fragmented forests. Thus, regional forest management practices and biodiversity conservation communities should comprehensively assess the impacts of forest losses and fragmentation on biodiversity according to the particular requirements of habitats requested by the individual species. For example, forest management needs to take into account the minimum area requirements and connectivity of habitats for certain organisms' survival and movement (Robbins et al., 1989).

6. Conclusions

This work has succeeded in developing the forest disturbance products using a vegetation change tracker model, quantifying the major changes in forest loss and regeneration for both federal forests and nonfederal forests in Alabama, USA, and ultimately creating a dense temporal profile of forest change and fragmentation for the state of Alabama. The successful description of pattern change accompanying forest loss and fragmentation provides a critical component of habitat analysis. At a regional scale, these changes may result in the elimination, displacement, or enhancement of species populations. Additionally, the identification of statistical relationships between forest fragmentation and forest logging and regeneration practices is important to facilitate future forest landscape management and monitoring actions in this heavily forested area. It is our belief that this project, which has successfully demonstrated the power of dense temporal sampling using Landsat data for tracking large area forest change and fragmentation patterns, is unique. We believe that this work will provide useful information to local land use managers interested in developing ecologically sustainable forest management strategies and biodiversity conservation practices.

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